The Multi-average Method to Accurately Estimate TEOAE Parameters

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ABSTRACT-**This study proposed the multi-average method to estimate the TEOAE parameters more accurately. The correlation between repeated measurements (reproducibility) was evaluated to see the performance. Results showed that the standard deviations of the correlation estimated by the proposed method were smaller than those by the typical method.**

I. INTRODUCTION

Transiently-evoked otoacoustic emissions (TEOAEs) are the acoustic signals produced by the inner ear in response to transient acoustic stimuli [1]. Because TEOAEs are altered in individuals with hearing loss [1], [2], the test of them have been widely used for newborn hearing screening recently. Unfortunately, the time-varying characteristic and inter-subject variability of TEOAEs make the difficulty in building the relationships between specific TEOAE measures and hearing losses. As a result, many TEOAE parameters such as TEOAE level, TEOAE/Noise, and correlation between repeated measurements (reproducibility) have been estimated [3]; however, noise contamination in TEOAE tests makes the difficulty in accurate estimation [4].

In the typical structure of one TEOAE test, many responses were evoked and alternatively distributed into two buffers, and two TEOAE signals were obtained by averaging these evoked responses in the two buffers, respectively. The TEOAE parameters were then estimated by the two TEOAE signals to determine the pass or fail of this test. However, it could be shown that the estimation accuracy was seriously influenced by the waveform of the TEOAE signals, which were the summation of the respective averaged noise signal and the true TEOAE signal. Therefore, even with one set of noise signals, different averaged noise signals would result from different combination of noise to be averaged, so that different TEOAE signals would be obtained. That's one important reason to the inaccuracy of the estimation.

This paper proposes a multi-average method to estimate the TEOAE parameters. In this method, N pairs of buffers instead of only two were used to store the total evoked responses, so that N pairs of TEOAE signals could be obtained. Therefore, for each kind of TEOAE parameter, N values could be obtained and averaged, and the estimation accuracy could be increased. In this paper, the reproducibility was estimated with the typical method and the multi-average method, respectively, to evaluate the performance.

II. MATERIALS AND METHODS

A. TEOAE Acquisition

Our own acquisition system for the TEOAE signals was developed. This acquisition system included a personal computer (PC) equipped with Intel Pentium CPU, a Loughborough Sound Images' (LSI) PC/C32 control board and an Etymotic Research's ER-10C acoustic-electric transformation system. A human-machine interface, which was programmed with the Borland C++ Builder software, was established on the personal computer. The stimulus generation and the acquisition of TEOAE signals were both controlled by the LSI PC/C32 control board. The ER-10C system that includes the microphone and sound source was used as the acoustic-electric transformation system.

Regarding the acquisition of TEOAE signals, we referred to the procedure adopted in previous studies [2], [5]. During the acquisition, the following settings were used. (1) The 80-μs acoustic impulses (clicks) with intensity of 80 dB sound pressure level (SPL) were used to stimulate the cochlea at a rate of 50/sec, and the derived nonlinear response (DNLR) [5] method was used. (2) The ER-10C system was set with the gain of 40 dB. (3) The evoked responses to the acoustic impulse were filtered by a fourth-order low-pass filter with cutoff frequency of 10.6 kHz and with unity gain. (4) The filtered evoked responses were then sampled at a rate of 25 kHz, and 512 samples were obtained per response. (5) The samples were windowed using the 2.5 ms-20.5 ms response window which had 2.5 ms cosine onset and offset, and were filtered by a digital bandpass filter with the bandwidth from 600 to 6000 Hz. (6) The noise rejection threshold was set at 50 dB SPL. The four evoked responses associated to each set of the four-clicks stimuli were averaged for every four-clicks set, and each resulting averaged response will be referred to as the subaveraged response throughout the text. These subaveraged responses were alternately sent to two different buffers (A and B), and the TEOAE acquisition for individual ear was complete after each buffer collected 256 subaveraged responses. In the typical method, two TEOAE signals would be obtained by averaging the subaveraged responses in the two buffers, respectively. The all evoked responses for this study were collected from 3 normal ears of three adults, and they were measured within general laboratory without sound proof.

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Abstract

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B. Multi-average Method

The block diagram of the multi-average method is shown in Fig. 1.

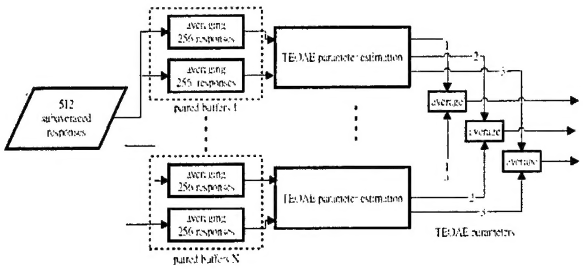

Fig. 1 Block diagram of the multi-average method

For each ear, this method didn't only use two buffers (A and B) to store the total 512 subaveraged responses, but it used N pairs of buffers instead. As to the distributing of the 512 subaveraged responses into these buffers, it must meet the requirement that different buffers must contain different combination of 256 subaveraged responses, and the paired buffers can't contain duplicate subaveraged responses. The goal of this requirement is to obtain N different paired TEOAE signals for further processing, which all these TEOAE signals were the averages of 256 subaveraged responses, respectively. In this paper, the requirement was met by randomly distributing the 512 subaveraged responses into each pair of buffers with 256 ones in each buffer.

After the distributing procedure, N paired TEOAE signals could be obtained by averaging the corresponding 256 subaveraged responses in the N paired buffers. To estimate one TEOAE parameter, each paired TEOAE signals could be used to estimate one value, and N values could be obtained with N paired signals. Finally, the average of these N values were used to substitute for the single value in the typical method.

C. Evaluation of Performance

To evaluate the performance of the multi-average method, the simulated noise without and with the TEOAE signal were tested. The noise in each subaveraged response was simulated using the following steps. (1) Total 512 random numbers were originally generated according to normal distribution with zero mean and standard deviation σ_N. (2) These 512 numbers were weighted and filtered using the same time window and bandpass filter as those used in step 5 during TEOAE acquisition.

In the first simulation, one simulated noise was added to one noise-free TEOAE signal to produce one subaveraged response, and total 512 subaveraged responses were generated for one noise-free TEOAE signal. The noise-free TEOAE signals were simulated with real TEOAE signals recorded from 3 normal ears and with reproducibility higher than 90%; the σ_N of the simulated noise was adjusted to meet desired SNR. In the second simulation, 512 simulated noise were just taken as the 512 subaveraged responses. In both simulations, the generated 512 subaveraged responses were treated with the typical method and with the multi-average method to obtain one pair and N pairs of TEOAE signals, respectively. Each paired TEOAE signals were then decomposed into three octave bands centered at 1000, 2000, and 4000 Hz, thus obtaining three pairs of frequency specific components. Finally, the correlation coefficient between each pair of frequency specific components was estimated. As a result, with 512 subaveraged responses, three frequency-specific correlation coefficients were obtained for the typical method, and N sets of three frequency-specific correlation coefficients were obtained for the multi-average method. Three average values for these N sets of coefficients were then calculated. Both simulations were repeated 1000 times, and the distributions of the estimated correlation coefficients were calculated. In this paper, the N in the multi-average method was selected as 4.

III. RESULTS

Fig. 2 demonstrates the distribution of the correlation coefficients obtained from the bandpassed simulated noise centered at 1000 Hz. The distributions obtained by the typical method and by the multi-average method were compared. It could be observed that the distributions were more concentrated for the multi-average method.

Table 1 and Table 2 list the comparison of the correlation distributions obtained by the multi-average method and by the typical method, which Table 1 and Table 2 were obtained from simulated noise with and without real TEOAE signals, respectively. In both tables, means and standard deviations (SD) of the distributions were compared. It could be observed that the standard deviation of the correlation estimated by the multi-average method reduced for all signals and for all bands. Besides, the means were not influenced by the proposed method.

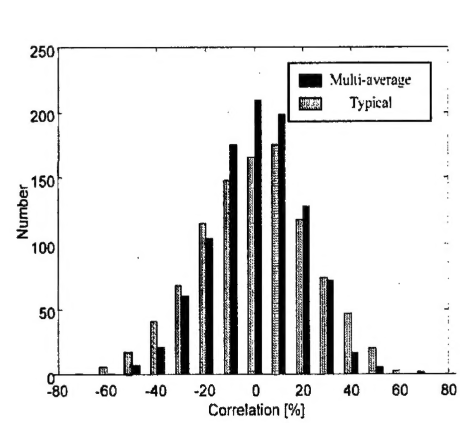

Fig. 2: Distributions of the correlation coefficients obtained by the multi-average method and by the typical method, respectively. The distributions were obtained from bandpassed simulated noise centered at 1000 Hz with 1000 realizations.

TABLE I

CORRELATION DISTRIBUTIONS OBTAINED FROM SIMULATED NOISE BY THE TYPICAL METHOD (TYPICAL) AND BY THE MULTI-AVERAGE METHOD (NEW).

	Mean (%)		SD (%)	
band	typical	new	typical	new
1000	0.84	0.83	22.99	18.51
2000	0.60	0.09	16.57	13.20
4000	0.13	-0.11	11.84	9.29

TABLE II

CORRELATION DISTRIBUTIONS OBTAINED FROM SIMULATED NOISE PLUS TEOAE SIGNALS BY THE TYPICAL METHOD (TYPICAL) AND BY THE MULTI-AVERAGE METHOD (NEW).

		Mean (%)		SD (%)	
Signal ID	band	typical	new	typical	new
1	1000	96.57	96.54	1.26	0.65
	2000	80.69	80.81	4.53	2.72
	4000	70.53	70.73	4.88	3.15
2	1000	93.56	93.56	2.27	1.22
	2000	75.69	75.66	5.63	3.33
	4000	83.52	83.50	2.82	1.73
3	1000	96.41	96.39	1.27	0.67
	2000	78.73	78.52	4.90	3.04
	4000	77.14	77.04	3.88	2.31

IV. DISCUSSIONS AND CONCLUSIONS

This paper proposed the multi-average method to estimate the TEOAE parameters more accurately. One of the TEOAE parameters, correlation between repeated measurements (reproducibility), was evaluated to see the performance. Results have shown that, with the multi-average method, the standard deviation of the correlation estimation was greatly reduced.

By the time-varying characteristic and the inter-subject variability of TEOAEs, it is difficult to build the relationships between specific measured TEOAEs and hearing losses. However, while many studies focused on finding these relationships by comparing many TEOAE parameters, the noise contamination makes the difficulty in estimating these parameters accurately. This paper just provides a more accurate way to estimate the parameters, so that the relationships will be built more effectively.

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